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STATUS REPORT
on
Low Cost Avionics
for the
Global Positioning System -

NASA Grant NSG-1374

August 1st, 1977

Prepared by

Dr. John H. Painter
Dr. Phillip S. Noe
Dr. V. Thomas Rhyne

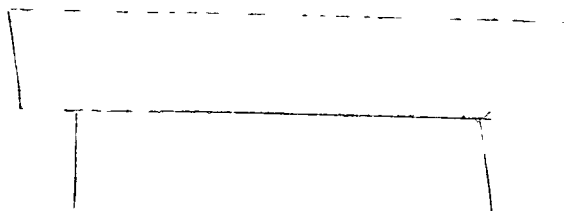
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(NASA-CP-154004) LOW COST AVIONICS FOR THE
GLOBAL POSITIONING SYSTEM (Texas A&M Univ.)
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Status Report
1 August 1977

This status report on "Low Cost Avionics for the Global Positioning System," NASA Grant NSG 1374, is forwarded at this time to report conclusions on several recent investigations. Also, ongoing work is detailed.

Costas Loop and Correlation Analyses

The key to feasibility and usefulness of the single-channel GPS receiver is the speed with which code and carrier synchronization may be established as the receiver cycles over a sequence of satellite signals. Thus a considerable amount of effort has been spent on modeling and simulating the Costas Loop, together with a fast algorithm for estimating and forcing "lock".

Enclosed is a copy of TCSL Research Memorandum 77-06, "Costas Loop and Correlation Analyses for the Low Cost GPS Receiver." This report is composed of two engineering reports prepared by Captain David A. McClung, U.S. Army, in partial fulfillment of the requirements for the degree, Master of Engineering, at Texas A&M University. The report covers the mathematical modelling and Monte Carlo (FORTRAN) simulation of two types of Costas Loops in noise, including a correlation detector and algorithms for sweeping the loops into lock.

The initial approach to the acquisition problem, which McClung has followed, is to sweep the Costas Loop VCO as rapidly as possible over a 10 KHz. frequency uncertainty range, and estimate the frequency at which maximum correlation occurred. Then the VCO is reset to the estimated frequency and the loop is

allowed to "pull" into lock naturally. In the limited time available to him he was able to obtain simulation results only for one particular sweep rate and one particular value of correlator bandwidth.

McClung's first results show that a 10 Khz. uncertainty range can be swept in 70 milliseconds. However, his noiseless linear estimate of maximum correlation frequency had a worst case error of 150 Hz. With this tuning error, the loop pull-in time is 12 and .42 seconds for a 100 Hz. loop bandwidth, for the Sine Loop and Tangent Loop respectively. With a 70 millisecond sweep and 2048 trial code correlations, the maximum time devoted to sweeping would be 141 seconds. So 0.5 seconds for the loop to pull in to final lock does not seem comparatively excessive. However, the total worst case time to lock of 141.5 seconds is absolutely excessive for nominal use. The design goal is for cycle times between satellites on the order of 1 second.

It is apparent that in order to reach the design goal of 1 second between satellites for nominal operations, both the frequency uncertainty and the code delay uncertainty must be drastically reduced. Only by limiting the range of the frequency sweep and the number of trial correlations can the desired acquisition time be realized. To reduce the sweep range and number of trial correlations will require computational aid from the receiver's microcomputer processor.

After each satellite has been acquired once, the 50 BPS data read, and the satellite ephemerides stored, then the frequency uncertainty due to satellite doppler may be largely eliminated. This requires that a rough estimate of the users position be available. At that point the A Priori frequency uncertainty, or sweep range, of 13,532 Hz can be reduced by 9767 Hz. to 3,765 Hz. Since

a relative frequency estimator is used in the Costas Loop it is quite likely that the sweep range can be further reduced by partially eliminating the uncertainty due to oscillator long term stability (945 Hz.) and aircraft doppler (2820 Hz.)

Assuming a one-second cycle time between satellites, a sequence of four satellites and a worst case aircraft velocity of 600 statute miles per hour, the worst case code delay uncertainty for two consecutive acquisitions of the same satellite is 2144 meters or 7.154 microseconds, without knowledge of the aircraft velocity vector. This is equivalent to 7.32 PN bits or 14.6 trial correlations

Suppose that, conservatively, we set the code delay uncertainty at 20 trial correlations and the frequency uncertainty at 3.765 Hz. (the satellite Doppler uncertainty has been eliminated). Let us allow 0.5 seconds for 20 trial correlations and frequency sweeps. This requires a sweep time of 25 milliseconds or 150,000 Hz/sec sweep rate, which is approximately the rate demonstrated by McClung. Thus, McClung's results are applicable to the single-channel GPS receiver under realistic assumptions for Doppler/Delay-aiding acquisition

The work which will be pursued in the Costas Loop area during the remainder of Phase I (until October 1, 1977) will be to refine the lock-frequency estimation algorithm and to evaluate its performance in the noise environment to be expected under nominal conditions, which is for a signal to noise spectral density of 38.4 dB/Hz. The correlation filter bandwidth may be reduced somewhat from the value demonstrated by McClung, 314 Hz, depending on performance. Also, the Costas-Loop bandwidth may be adapted from its acquisition value of 100 Hz to its tracking value of 10 Hz. during the maximum pull-in time. It

will be determined whether to acquire the loop in the Sine configuration or in the Tangent configuration. In addition, the hold-in behavior of both loops will be evaluated when they are subjected to phase accelerations (frequency ramps) after being initially locked. This evaluation will determine whether the Tangent Loop is more immune to dynamics than the Sine Loop.

Keplerian Orbit Simulation and the Navigation Algorithm

Ephemerides data for the 24 GPS satellites had previously been obtained from a circular deterministic orbit algorithm obtained from Dr. Thomas Wu and Major Kenneth A. Myers of the USAF Avionics Laboratory at WPAFB, Ohio. Actual satellite data transmitted in Data Block II are the Keplerian orbit parameters that are required to solve the Keplerian orbit equations in an ECEF (earth centered earth fixed) coordinate system.

The satellite orbit parameters range from 8 to 32 bits of accuracy. Memory constraints and computation time dictated a desire to create a micro-processor architecture based on a 32 bit floating point system (24 bit mantissa and 8 bit exponent and sign). Thus a major purpose of this research was to determine the affect of truncating 32 bit data parameters down to 24 bits.

The initial simulation produced ephemeris data for a single satellite in one complete 12 hour orbit. Two runs were made one with 32-bit precision and one with 24-bit precision. The RMS difference was defined as the distance error of the 24-bit implementation. The maximum error encountered in a 12-hour orbit is 4990 feet.

A subsequent simulation was performed to determine the smoothing effect (if any) of the Navigation Algorithm on the ephemeris error. A simulated USAF C5A aircraft flight from California to Hawaii showed fixes taken at 30 second intervals to be less than 100 feet in error 82% of the time and less than 325

feet all of the time. These results compare almost exactly with the previously produced noisy model simulation for the circular orbit algorithms

These findings suggest that the noise completely obscures the truncation error of the algorithms, however, we have subsequently determined that the reverse is actually the case.

Double precision (56 bit mantissa) runs were made without noise substantiating algorithm accuracy obtained at WPAFB previously. Single precision (24 bit mantissa) runs were made without noise and nearly identical results were obtained as the runs made with noise. That is, typical errors of 100 feet or less occur in 82% of the fixes with or without noise if only 24 bits of precision are used in the computations. Hence, it is conclusive that (with the noise models used) truncation (or round-off error) is the dominant factor of error production for a 24-bit computer system in the low cost GPS receiver.

The existing navigation software has just been converted to operate on the DEC11/40 USAF computer at Texas A&M. Experiments have been defined that will be used to modify the navigation software from its present parallel input of satellite information to a low-cost single-channel serial input format. Satellite selection will also be studied. The existing algorithm for selection will be used to obtain a set of four satellites with good GDOP. Then these four satellites will be retained until one (or more) disappears from view. GDOP and position error will be recorded to determine the effectiveness of this procedure. A new selection procedure will be used when a satellite disappears to determine if any of the original set can be regained. Again GDOP and position error will determine the effectiveness of the procedure.

Hardware Effort

The hardware research program has concentrated on the microprocessor-controlled phase shift circuitry that permits the locally generated Gold code to be cross-correlated with the received Gold code in order to obtain range. The phase shift circuitry includes a divide-by-44 counter, a digital pulse cancellation subsystem, and a variable-phase divide-by-35 counter system. These three systems have been constructed in prototype form by Mr. O. Ladipo, an Electrical Engineering graduate student. Typical 7400 TTL digital devices were used, limiting the prototype to several MHz in frequency. The performance was satisfactory at that frequency range, however, and translation to the 35 MHz range is not expected to be difficult. Mr. Ladipo has completed an engineering report on his work, and copies of that report are enclosed.

Additional study has been directed toward the generation of the various Gold codes used by each of the 24 satellites. In the next reporting period the generating polynomials for each code will be tested, and hardware/software subsystems for generating these codes under microprocessor control will be developed. Also, a systematic approach to initializing the sequential code generator to any desired phase will be developed.

Selection of Receiver Parameters

Basic Assumptions

Worst Case Satellite Radial Velocity	2,078 MPH (stat.)
Highest Aircraft Velocity	600 MPH (stat.)
Oscillator Long Term Stability (Aircraft):	3×10^{-7}

Calculations

The oscillator output frequency is

$$f_o = F + \Delta \pm \epsilon \quad \epsilon \approx 3 \times 10^{-7} \times F \quad (1)$$

where

$$F = \frac{1575420000}{44} = 35805000. \text{ Hz.} \quad (2)$$

and Δ is chosen as a design parameter. Note that $44F$ is the satellite transmitter frequency, equal to 1575.42 Mhz.

The second I.F. frequency, which is the Costas Loop input frequency is chosen to be less than or equal to 30 KHz. under all conditions. This is to give the possibility of eventual total digital realization for the Costas Loop

The normalized radial velocity between aircraft and satellite (worst case) is

$$\frac{V}{C} = \frac{V_a}{C} + \frac{V_s}{C} = \frac{600 + 2078}{186219 \times 3600} = 3.99 \times 10^{-6} \quad (3)$$

The total tuning increment for the Costas Loop is given by

$$\begin{aligned} \Delta f &= (2)(44)(\epsilon + F(\frac{V}{C})) \\ &= 88(3 \times 10^{-7} + 3.99 \times 10^{-6})35805000 \\ &= 13532 \text{ Hz} \end{aligned} \quad (4)$$

The lower end of the second I.F band is then

$$30,000 - 13,532 = 16,468 \text{ Hz}$$

and the center of the band is

$$(30,000 + 16,468) - 2 = 23,234 \text{ Hz}$$

Thus Δ is solved for as

$$\Delta = \frac{23,234}{44} = 528.0 \text{ Hz.} \quad (5)$$

The first I F passband is defined by

$$\begin{aligned} f_{1f} &= F + 45\Delta \pm (45\varepsilon + 44 F(\frac{V}{C})) \\ &= 35828760 \pm 6,769 \end{aligned} \quad (6)$$

Thus, the I F center frequency and bandwidth are respectively

$$F_{1f} = 35.828760 \text{ Mhz}$$

$$BW = 13.5386 \text{ Khz}$$

The relationship between first I.F bandpass and oscillator frequency is shown in Figure 1

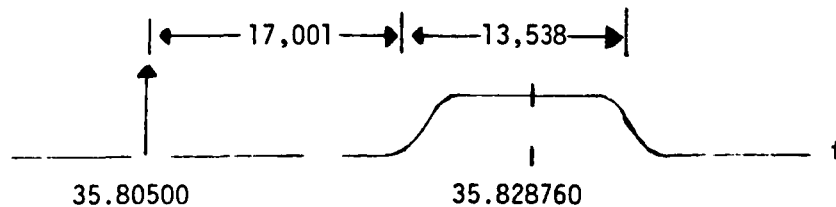
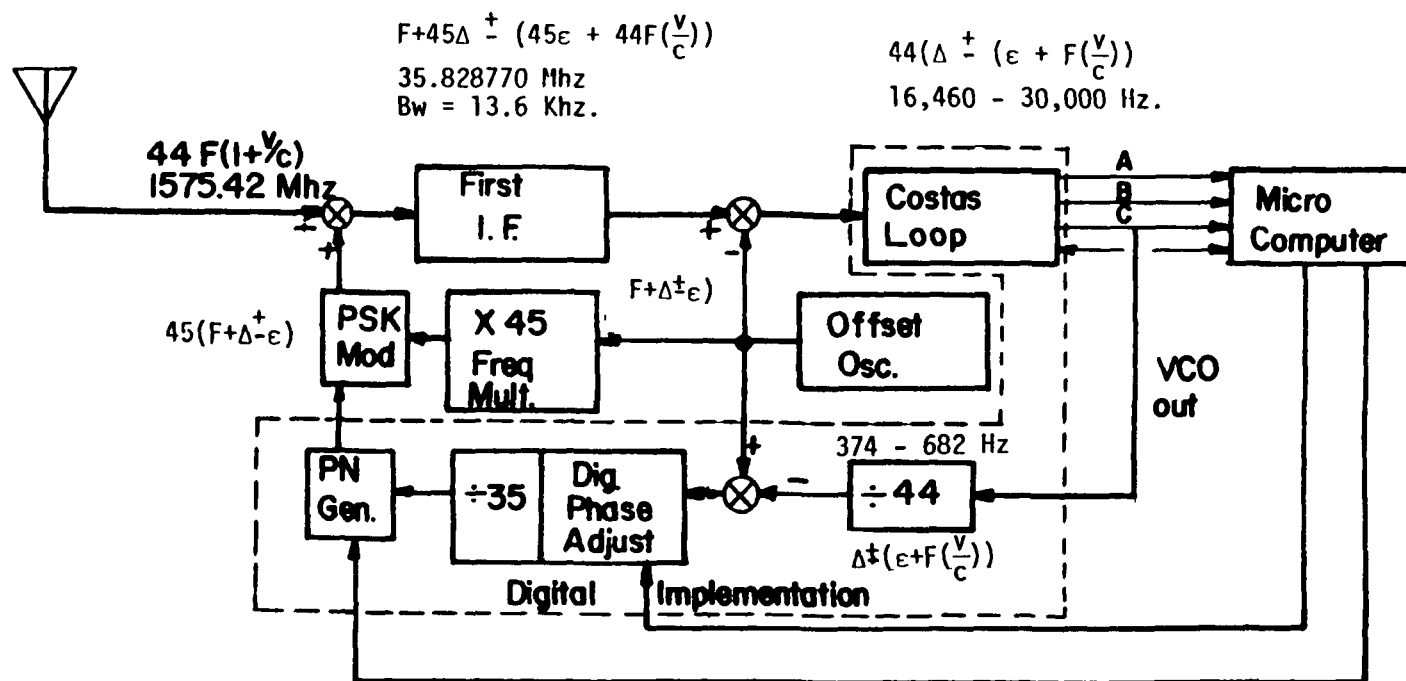


Figure 1. Relation of I F. to Oscillator Frequencies



$F = 35.805000 \text{ Mhz.}$
 $v/c = 3.99 \times 10^{-6}$
 $F(v/c) = 143 \text{ Hz.}$
 $\Delta = 528.0 \text{ Hz.}$
 $\epsilon = 10.7 \text{ Hz.}$

LINK MARGIN ANALYSIS

1. Transmitter Power	20 Watts (Radiated)	13.0 dbw
2. Transmitter Circuit Loss		-0- db
3. Transmitter Antenna Gain		13.7 db
4. Transmitter Antenna Pointing Loss		-0- db
5. Space Loss	$f = 1575.4 \text{ Mhz.}, r = 25824 \text{ km.}$	-184.6 db
6. Antenna Polarization Loss	2 db ellipticity XMT	-1.4 db
7. Receiving Antenna Gain	3 db ellipticity Rev.	-2.0 db
8. Receiving Antenna Pointing Loss		-0- db
9. Receiving Circuit Loss		-1.0 db
10. Net Loss Link (Add 2 through 9)		-175.3 db
11. Total Received Power (Add 1 plus 10)		-160.3 dbw
12. Receiver Noise Spectral Density	$T = 625 \text{ }^{\circ}\text{K}$ $F = 5 \text{ db}$	-200.7 dbw/Hz.
13. Received Signal/NSD (11 minus 12)		+38.4 db /Hz.
COSTAS LOOP		
14. Costas Loop BW	10 Hz.	10 db Hz.
15. Costas Loop SNR (13 minus 14)		+28.4 db
16. Required Loop SNR		db
17. Carrier Margin (15 minus 16)		db
DATA		
18. Bit Period	sec.	-17 db sec.
19. Received Energy/NSD, E/No (13 plus 18)		+21.4 db
20. Required E/No		db
21. Data Margin (19 minus 20)		db